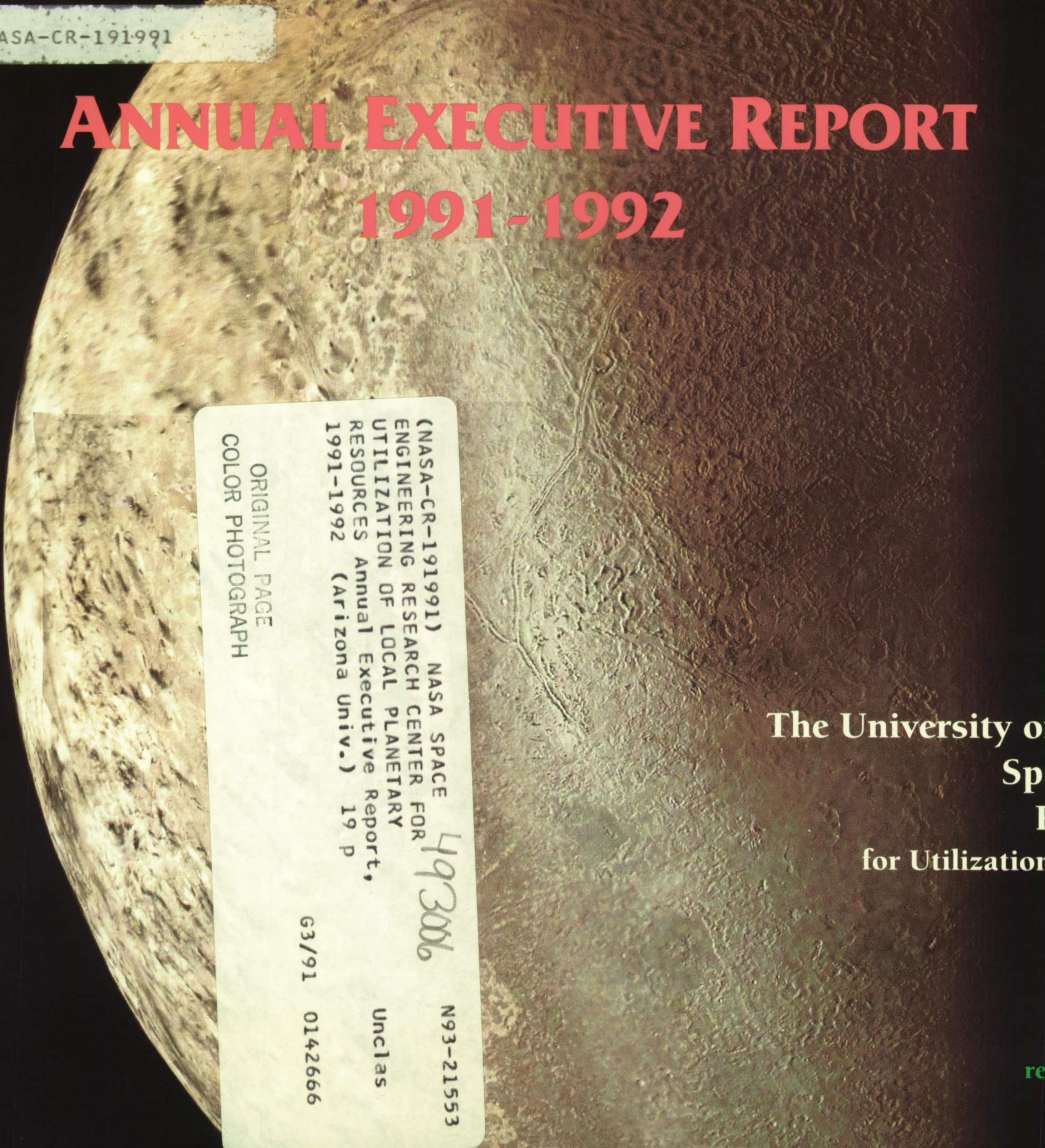
ANNUAL EXECUTIVE REPORT
1991-1992



The University of Arizona/NASA
Space Engineering
Research Center
for Utilization of Local Planetary
Resources

a national center for
space engineering,
research, and education

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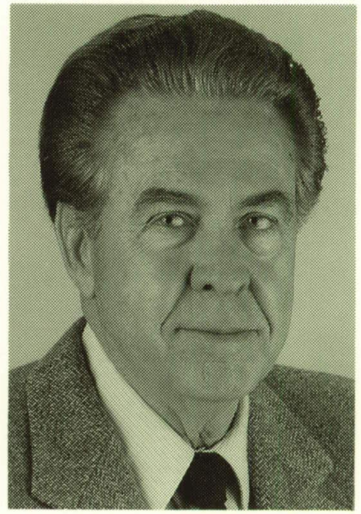
INTRODUCTION

In the four years since the University of Arizona/NASA Space Engineering Research Center was established, it has become recognized as a national and international center for space resources research, development, and education. Perhaps equally important, it has become recognized within NASA as the premier center of activities in the area popularly known as In-Situ Resource Utilization (ISRU) or Indigenous Space Materials Utilization (ISMU). By providing a central focus, the Center has served a wide range of NASA needs in this important field of space technology development.

A team of outstanding scientists and engineers devoted to continuing work in the field has been assembled and many publications of their work issued. A large number of dedicated graduate and undergraduate students have been trained and a number of popular new space science and engineering courses and degree options introduced to the University of Arizona's curriculum. Annual symposia and several specialized workshops of high quality have been sponsored by the Center. And every major aerospace industrial organization in the country has become involved in supporting the Center's program.



Dr. Terry Triffet, Director

The key element in our philosophy of research is emphasis on a practical approach, interweaving engineering and science skills and knowledge. The hands-on training emphasized in the Center's research projects has attracted an excellent corps of graduate and undergraduate students. Our strong commitment to education is also inextricably interwoven with all SERC activities. After screening for scientific soundness — which often involves separate science projects — technical feasibility is established through preliminary research. The next step is thorough testing of the components and assembled systems under anticipated operating conditions. Data from such testing are mandatory for proof-of-concept, and are obtained from carefully designed testbeds.

The testbed approach involves the principal processing unit and supporting components assembled in a single small system. Lessons learned from experiments performed on this are then used to design and operate larger scale testbeds. Two are

currently in operation at the Center: one for oxygen, hydrogen, and methane production from carbon dioxide and water; another for the production of oxygen and structural elements from lunar soil. After a concept graduates through these two testbeds, it is incorporated in a breadboard of a realistically packaged system and production specifications are prepared.

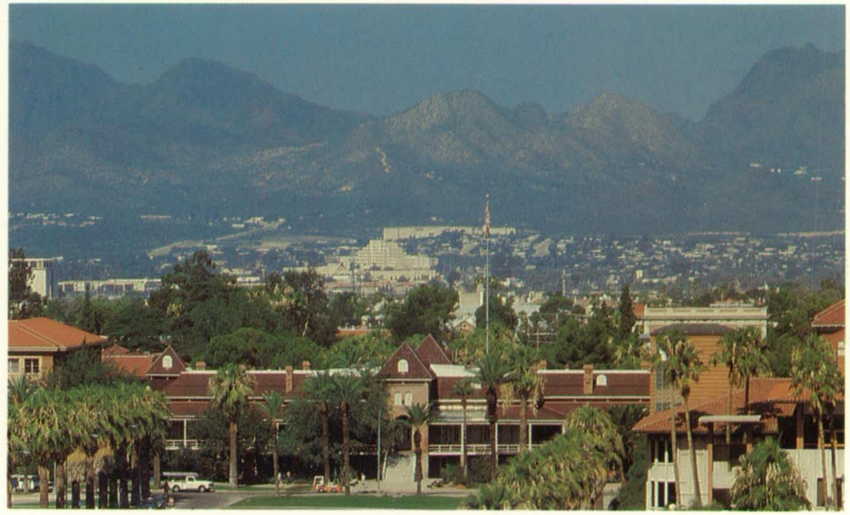
Major benefits derived from our research projects include the opportunity to work with private-sector industry in the development of technically and economically viable technologies and hardware. Our efforts in this regard have made UA/NASA SERC the natural meeting place for space resources research interests in academia, industry, and government.

SERC Headquarters

In the sections that follow, the historic course of the Center is charted, and major accomplishments of the last year are noted. Details of the contributions of the Center's research, educational, and industrial outreach activities to the nation's space exploration and development program, as well as to the economy of the state, appear in our pending proposal for a five-year renewal of the basic NASA grant.

— *T. Triffet*

HISTORY AND PURPOSE



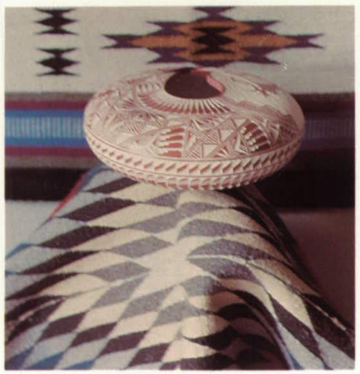
Old Main at the University of Arizona

In 1987, responding to widespread concern about America's competitiveness and future in the development of space technology and the academic preparation of our next generation of space professionals, NASA initiated a program to establish Space Engineering Research Centers at universities with strong doctoral programs in engineering. The goal was to create a national infrastructure for space exploration and development, and sites for the Centers would be selected on the basis of originality of proposed research, the potential for near-term utilization of technologies developed, and the impact these technologies could have on the U.S. space program. The Centers would also be charged with a major academic mission: the recruitment of topnotch students and their training as space professionals.

This NASA center of excellence allows the University of Arizona to utilize its talented faculty for the benefit of the U.S. Space Program and ultimately for a better society.

— Michael Cusanovich
Vice President for Research and Graduate Studies
University of Arizona

Tucson is a growing center of space-related activities, a modern city with a rich cultural heritage and unique arts



Proposals were submitted by every major engineering program in the U.S. After external technical review, a list of 115 proposals was trimmed to 25 finalists, which were announced in March 1988. Site visits by NASA representatives determined those schools with an ability to make significant contributions to NASA programs. Each Center would receive up to $500,000 in its first half-year of operation, and over $1 million annually for a minimum of four additional years. In late April 1988, nine of the universities were awarded Centers, among them the University of Arizona. Operations began here in early May 1988.

The proposal submitted by the University of Arizona was rated among the top two, and the site visit was highly successful, demonstrating broad engineering college and campus-wide capabilities, and strong administration support. Other factors worked in favor of the UA as well. The University has a unique concentration of knowledgeable scientists and engineers with a long tradition of working together on space-related projects. Tucson and Arizona constitute a world astronomical center, rich in observatories and talented scientists. In Tucson, the Space Business Roundtable was created to attract space-related industries and make the area a national center for such activities. Additionally, several space engineering activities of international repute were started here in the mid-1980s in the University of Arizona's Aerospace Engineering Department.

The role of the UA/NASA Space Engineering Research Center (SERC) is to develop the technologies necessary to produce a wide variety of useful products using the

materials and sources of energy that occur naturally in near-Earth space — thus the Center's subtitle: "for Utilization of Local Planetary Resources." This mission is fundamental to accelerating progress in space exploration and making space development activities economically feasible.

From this charge has grown a unique program of research and instruction dedicated to the use of space resources for propellants, and structural and shielding materials. In the little more than four years since UA/NASA SERC was established, a tightly integrated group of research and development projects in engineering and science has been created. The UA Center is the only place in the nation where In-Situ Resource Utilization (ISRU) is being reduced to hardware and engineering practice. A strong emphasis on student involvement in research projects has produced a remarkable level of enthusiasm, dedication, and creativity. As a result, the Center has drawn an excellent group of bright and energetic graduate and undergraduate students.

Another part of the Center's emphasis on education involves outreach to the community. SERC investigators give numerous lectures at elementary schools and high schools in Tucson and the surrounding area, featuring current information on national space activities and demonstrations of high-tech devices developed and used at the Center. Local middle school and high school interns often participate in SERC programs.

One emphasis of the Center's educational mission involves outreach to community schools. Here Dr. Kumar Ramohalli lectures at a local elementary school.

Central to the overall SERC mission are collaborative projects with private-sector industry partners to develop strategies and hardware for resources utilization in future space ventures. Despite federal budget uncertainties and a lack of NASA funding for the Space Exploration Initiative (SEI) in recent years, and the consequent

The Center is a meeting place for space experts from academia, government, and industry. The February 1992 conference examined potential technologies for a lunar outpost.

reluctance of major aerospace firms and other space-related industries to commit funds for external research, the Center has attracted more than $200,000 in the form of contract research support and Space Engineering Affiliate memberships. The Center has also received enthusiastic cooperation and support in kind (time and travel expenses of employees, publication expenses, etc.) from such organizations as Rockwell International, McDonnell Douglas, Fluor Daniel, Boeing Aerospace, Bechtel National, Lockheed Missiles & Space, Martin Marietta, and Ball Aerospace. Especially notable in this regard is the loan by Hamilton Standard Division of United Technologies of a compact water electrolysis unit (for the SERC Oxygen Production Testbed) valued at more than $350,000.

In the process of developing these relationships, SERC has come to be recognized as a meeting place for experts from academia, the private sector, and government agencies working in the field of space resources development. Last year, for example, the Center sponsored a much needed workshop in "Magmaelectrolysis of Indigenous Space Materials (MISM)" that brought together experts from Washington University, the University of North Dakota, Rockwell International, Fluor Daniel, and a number

of consulting firms. A formal report was published based on the discussions and papers presented at the MISM Workshop. Also, in February 1992, the Center's Third Annual Symposium was held. The program was organized around a possible Lunar Outpost scenario, and featured industrial technologies, systems, and components applicable to the extraction, processing, and fabrication of local materials. The Symposium, like the MISM Workshop, brought together representatives from academia and industry, but in addition to the customary space resources experts, investigators from outside the field whose knowledge could be applied to space development activities were included. Presentations came from a diverse group of specialists in fields such as minerals processing, environmental control, and communications. What resulted was a fresh look at a number of old problems, as well as a variety of new ideas and approaches.

A collection of abstracts was published for attendees at the Symposium, and the Proceedings volume containing all papers presented will soon follow. Since its founding, the Center has published a popular quarterly newsletter, featuring articles by SERC investigators and an annual issue devoted to student papers, and, of course, the Center regularly publishes progress reports containing technical information on its research and development projects.

As a center for space resources research, a leader in education, a partner with private-sector industry in the development of new technologies, and a forum for space experts and others with relevant knowledge, the University of Arizona/NASA SERC has in four short years become what a NASA spokesman recently termed one of the leading Centers in the University Space Engineering Research program.

Arizona and the University of Arizona/NASA Space Engineering Research Center have long been national leaders in the aerospace industry. SERC's academic mission will ensure our State has an ample supply of well-trained space professionals and its active research will ensure that we have developed the necessary technologies to utilize newly discovered space resources. If Arizona is to maintain its legacy of leadership in the aerospace industry in the 21st century, SERC will indeed play a vital role.

— Senator Dennis DeConcini

Dr. Kumar Ramohalli, Co-Director, Engineering

Thermal processing of soils in a special vacuum furnace

SERC ENGINEERING PROGRAM HIGHLIGHTS

The Space Exploration Initiative (SEI) has stimulated the United States' commitment to space. Had cost not been a major factor, it is clear that the nation would never have hesitated in that commitment. The single largest fraction of the cost is associated with the initial launch, which continues to be about $5,000/lb. from Earth to Low Earth Orbit (LEO). Despite valiant efforts, realistic projections still show a cost not less than $1,000/lb. While this is a dramatic improvement, it is still not sufficient by itself to take us to the Moon or to Mars. It is obvious that a new class of innovative advances are needed if our dreams are to become reality.

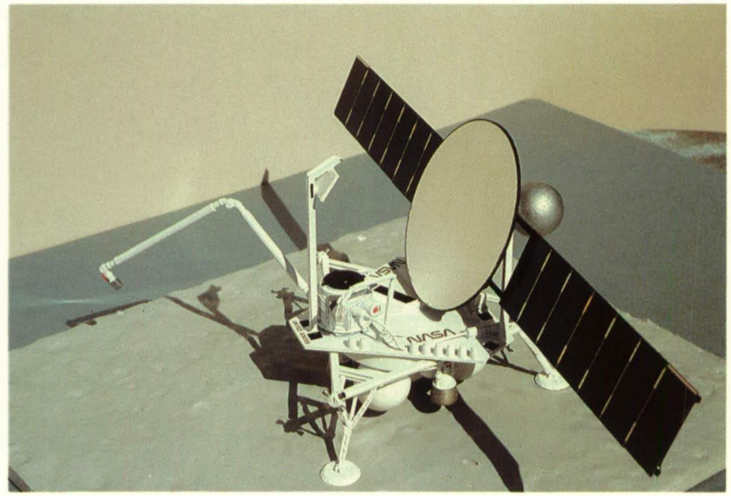
Fortunately, not only are such innovations feasible, but NASA has had the foresight and commitment to fund a Center at the University of Arizona dedicated specifically to such engineering advances. The basic innovation, of course, is In-Situ Resource Utilization (ISRU), where only a small fraction of the key hardware and usables are launched from Earth, and the rest are extracted/processed/built/assembled from local resources. While extraterrestrial resources are real, critical research and development are needed before committing important space missions to their availability and use. The UA/NASA Space Engineering Research Center has reduced to working hardware many of these important space technologies.

The fundamental plan for SERC engineering projects continues to focus on the manufacture of useful products from local resources, with emphasis on those that have oxygen, fuels, polymers, ceramics, and construction and shielding materials as the principal targets. The following constitutes a partial list of important engineering accomplishments in the last year:

— Engineering operation of a small-scale CO_2->O_2 testbed that produced over 10 grams of oxygen per day during several runs of over 100 hours, each using only a single electrolytic cell. Complete automation of controls, monitoring of various

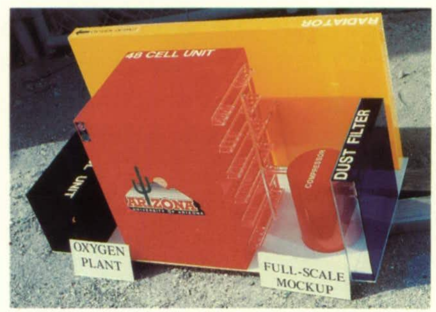
inputs/outputs and critical internal variables, diagnostics, and emergency shutdown in an orderly manner were also demonstrated. Moreover, 4-cell and 16-cell units capable of much higher rates of production were assembled and tested.

— Robotic handling of materials processing modules was initiated in the spring of 1992. Subsequent work resulted in the detailed design and modelling of a miniaturized self-contained processing module for small-payload precursor missions to the Moon and Mars. This lander unit utilizes an automated arm for sample collection, an intelligent control and communications system, and concentrated solar heating. The project was featured in *Space News* and was well received at the Artemis workshop in February 1992. Because the technology is crucial for many future ISMU units, the project is being continued.



Scale model of the proposed lunar lander

The 16-cell oxygen plant, which produces 0.2 kg of oxygen per day, in operation.



Full-scale mock-up of the oxygen plant (kg/day class)

— Demonstration of an apparent 800% increase in the conversion rates of ilmenite in a plasma-augmented reactor, including direct enhancement by solar radiation absorption.

— Experiments in the processing of glass ceramics from lunar resources established the feasibility of producing silicon-based polymers from indigenous lunar materials.

— Proof that test specimens of lunar soil with small amounts of metallic additives, recrystallized at moderate temperatures, exhibit an improvement of several orders of magnitude in ductility/tensile strength.

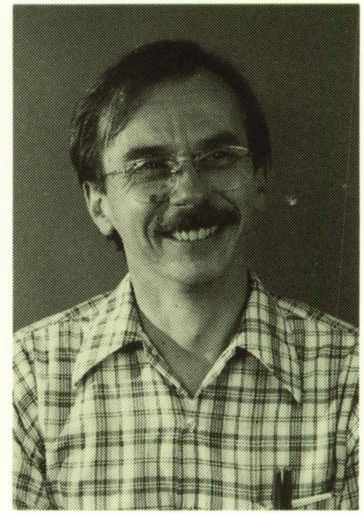
— Demonstration of a 200% increase in the carbothermal reduction of an iron bearing silicate through vapor deposition of carbon layers on particles of that material.

In summary, at the UA/NASA SERC, you will not find activities limited to gee-whiz pictures borrowed from others' successes. You will not find artists' renderings of tomorrowland in space. You also will not find small variations on business-as-usual. You *will* find innovative and realistic full-system hardware, with modern high-tech devices, developed by bright students. These *are* the future of economical space missions and settlements.

Many human benefits from space engineering are now being realized. While developments such as modern satellite communication, space-controlled navigation, and remote sensing are mind-boggling, we have only scratched the surface. The future will bring space manufacturing and many more developments, including advancements in space technologies. The University of Arizona/NASA Space Engineering Research Center will continue to be a national leader in making these advancements possible and will help Arizona advance in space engineering technologies.

— Ernest T. Smerdon (Member, National Academy of Engineering)
Dean, College of Engineering & Mines
University of Arizona

SERC SCIENCE PROGRAM HIGHLIGHTS, 1991-1992

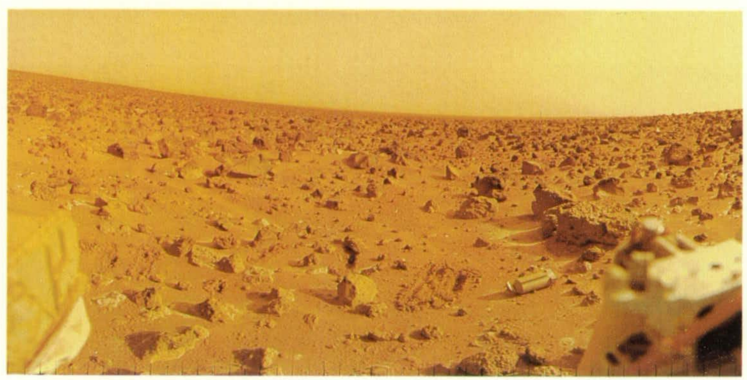


Dr. John Lewis, Co- Director, Science

The SERC science program is dedicated to the discovery and characterization of non-terrestrial resources, defining the natural materials and environments within which processing of these resources can occur, and to screening candidate processing schemes and transportation system architectures for the retrieval of these resources and delivery to their site of use.

During the past year we have reached a number of milestones in the science program. Prof. Singer and his co-workers in the Planetary Image Research Laboratory have completed an ambitious project for mapping the titanium abundance (ilmenite content) of the mare basins on the near side of the Moon. Prof. Lebofsky and Dr. Nelson have developed an application of Hapke theory for mineralogical interpretation of asteroidal and lunar spectra. Prof. Haskin and Dr. Colson (at Washington University) are now undertaking a scale-up of their apparatus designed to extract oxygen from lunar regolith materials by melt electrolysis using platinum electrodes, and are working on the problems of container stability and electrode consumption. Prof. Freiser and Dr. Muralidharan have developed a compact system and efficient procedure for extraction and separation of platinum-group metals to recover and recycle the "lost" electrode materials.

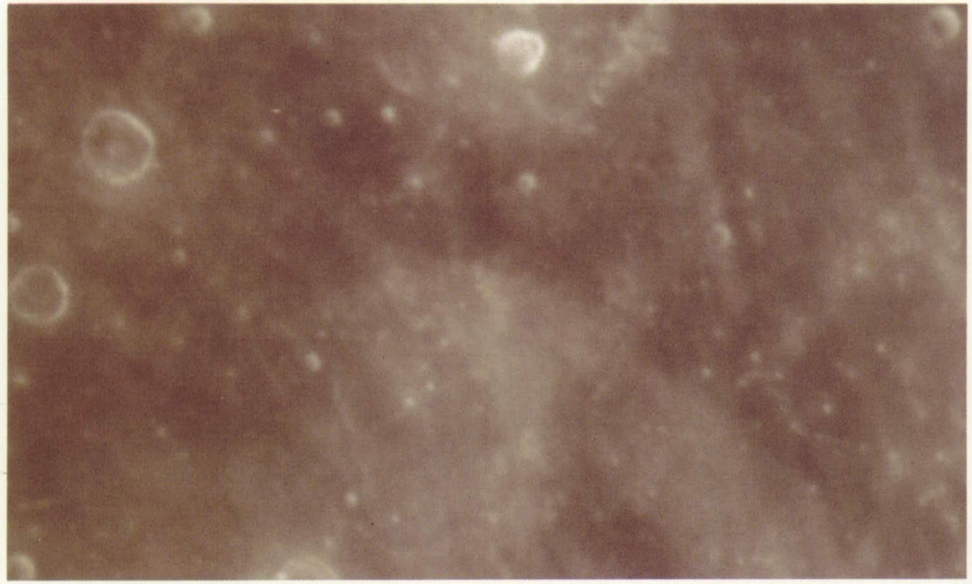
Prof. Lewis and Mr. William Jenkin have made substantial progress in understanding the extraction of ferrous metals from electrolysis cathode deposits, ilmenite reduction products, and magnetic-rake extracts of lunar and asteroidal regoliths via low-temperature volatilization of iron and nickel



Winter on Mars. Photo taken by Viking Lander II

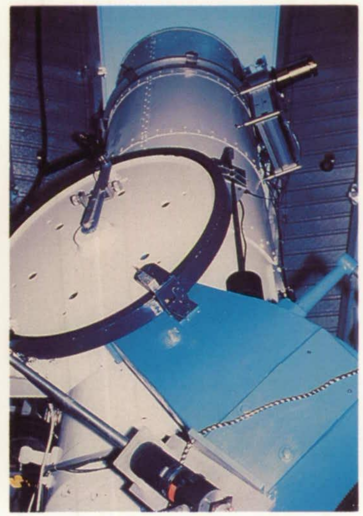
carbonyls. The CO reagent needed for this extraction fits well into a CO-CO_2 ilmenite reduction scheme.

The Spacewatch program has become fully operational, and has now discovered more than 24 near-Earth asteroids, including the nearest and smallest asteroids ever discovered. Spacewatch is filling in the gap in our knowledge of the abundances of Earth-approaching objects in the 10 to 1000 m



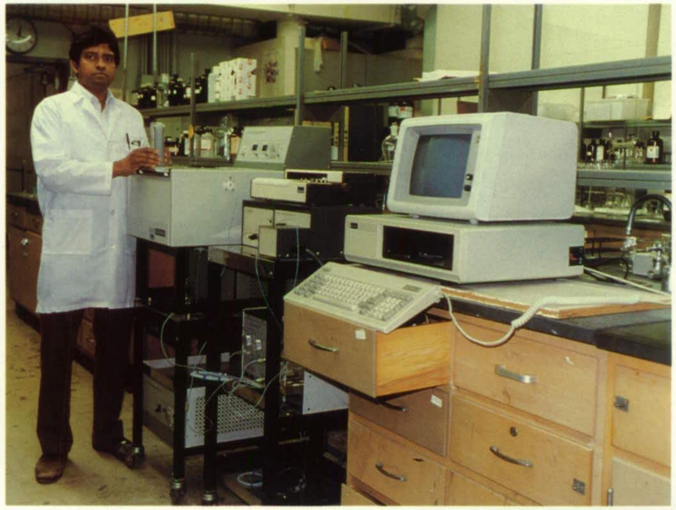
Lunar landscape: Image of western Mare Tranquillitatis taken at 730 mm with University of Arizona Tumamoc Hill 0.5-meter telescope. North is approximately in upper left.

The Kitt Peak observatory that houses the Spacewatch telescope



The 0.9-inch Spacewatch telescope

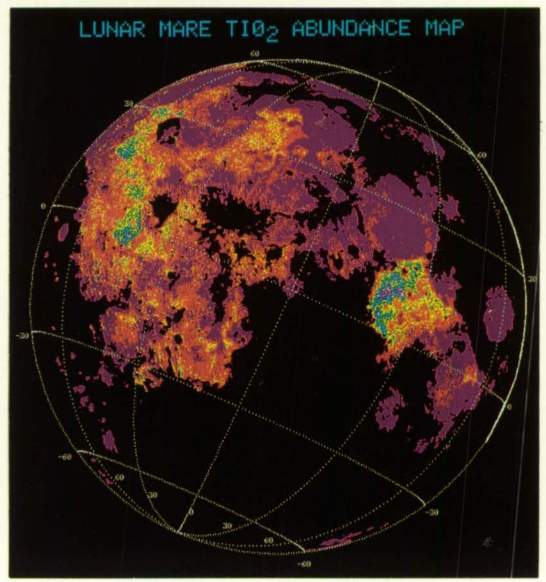
diameter range, confirming a dramatic excess of bodies less than about 30 m in diameter relative to a linear extrapolation of the Belt asteroid population line.



Dr. Muralidharan with apparatus for extraction and separation of platinum-group metals. The entire apparatus, including PC for data collection, is shown.

A detailed Monte Carlo simulation of the comet and asteroid bombardment of the Earth has been developed by Prof. Lewis which incorporates our new data on the numbers and compositions of these bodies. This model permits a new assessment of the hazards of Earth-crossing bodies from data originally collected to assess their resource importance.

Lunar Mare TiO2 abundance map (weight percent) derived from spectral imagery



Prof. Ganguly and Kunal Bose have developed equipment and procedures for studying the dehydration behavior of water-bearing minerals and applied their technique to the study of the dependence of outgassing rate on mineral grain size. Also, our improving understanding of the abundance and extractability of water in near-Earth asteroids has permitted a study of the transportation-system implications of the availability of large amounts of water in near-Earth space. This study demonstrates mass payback of roughly 100 tons of water returned to Earth orbit per ton of equipment launched from the Space Station for multi-flight missions to known near-Earth asteroids, and suggests that the most attractive resource in the inner solar system may be asteroidal water.

ECONOMIC IMPACT

The University of Arizona is one of the most successful institutions in the nation in winning grants from external sources of funding, and the research associated with these awards serves to attract the sort of high technology enterprises that significantly strengthen Arizona's economy. Moreover, a major component in the University's role as a research institution is the space-related science and engineering programs.

The UA/NASA SERC contributes to this effort by actively seeking interaction with and support from government and industry. It cooperates with the University in transferring patents and new technology into the private sector. It enthusiastically supports community organizations that seek to bring together diverse groups to create a space technopolis in Tucson and southern Arizona, and welcomes feedback from the community and from public officials. It seeks means for spinning off companies to continue R&D efforts commercially, and in every way possible supports the concept of early commercialization of space development.

The economic future of Tucson and Southern Arizona may well be linked to the development of space-related industries. With its programs in the sciences and with Tucson's identity as a center of astronomical research, Southern Arizona is destined to become a hub of space-related activity. The University of Arizona will play a key role. For example, the UA/NASA Space Engineering Research Center has already established itself as a leader in space industry development with its recruitment and training of students, its participation with the private sector in the development of space resources utilization technologies, and its active participation in Southern Arizona and around the nation to inspire interest in and spread knowledge about space engineering and sciences.

— Congressman Jim Kolbe

Figure 1

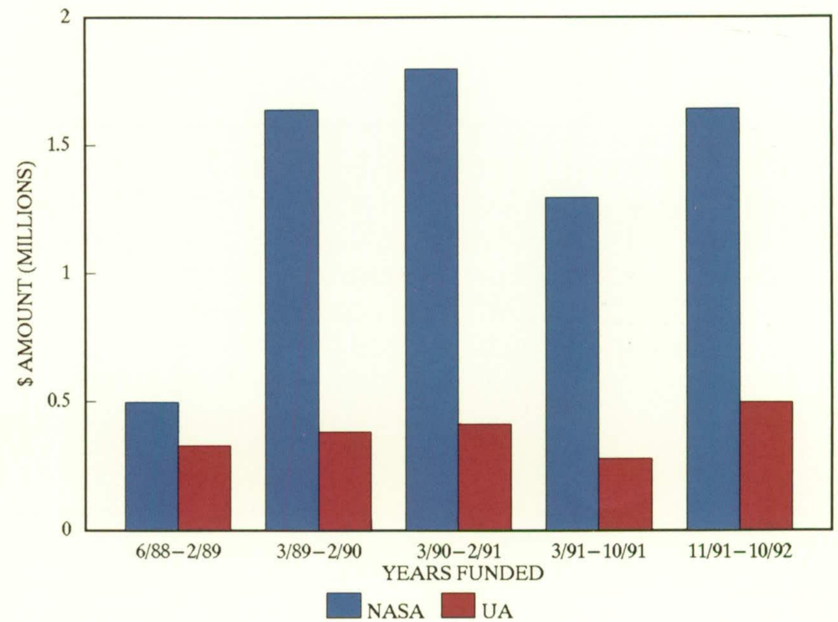
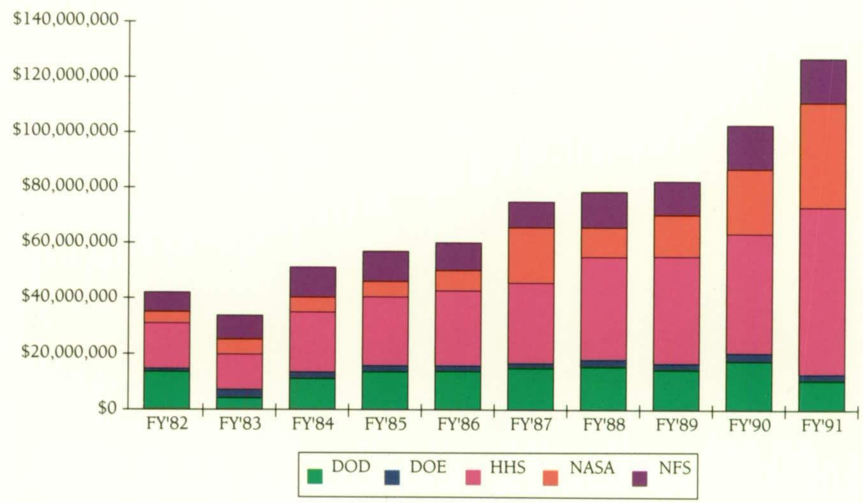


Figure 2



The University of Arizona/NASA Space Engineering Research Center plays a key role in making our state a center for space activities. The team of engineers and scientists associated with the Center has created a strong program of research and instruction in space resources development to train the next generation of space engineers and scientists. Along with its academic mission, the Center also actively seeks the involvement of private-sector industry in the development of commercially viable space technologies. This union of academia and industry can contribute significantly to Arizona's economic future.

— Governor Fife Symington

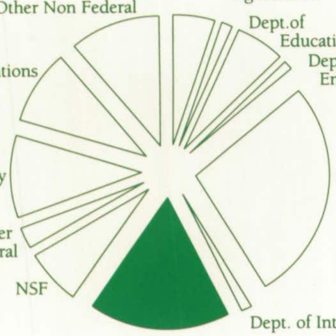
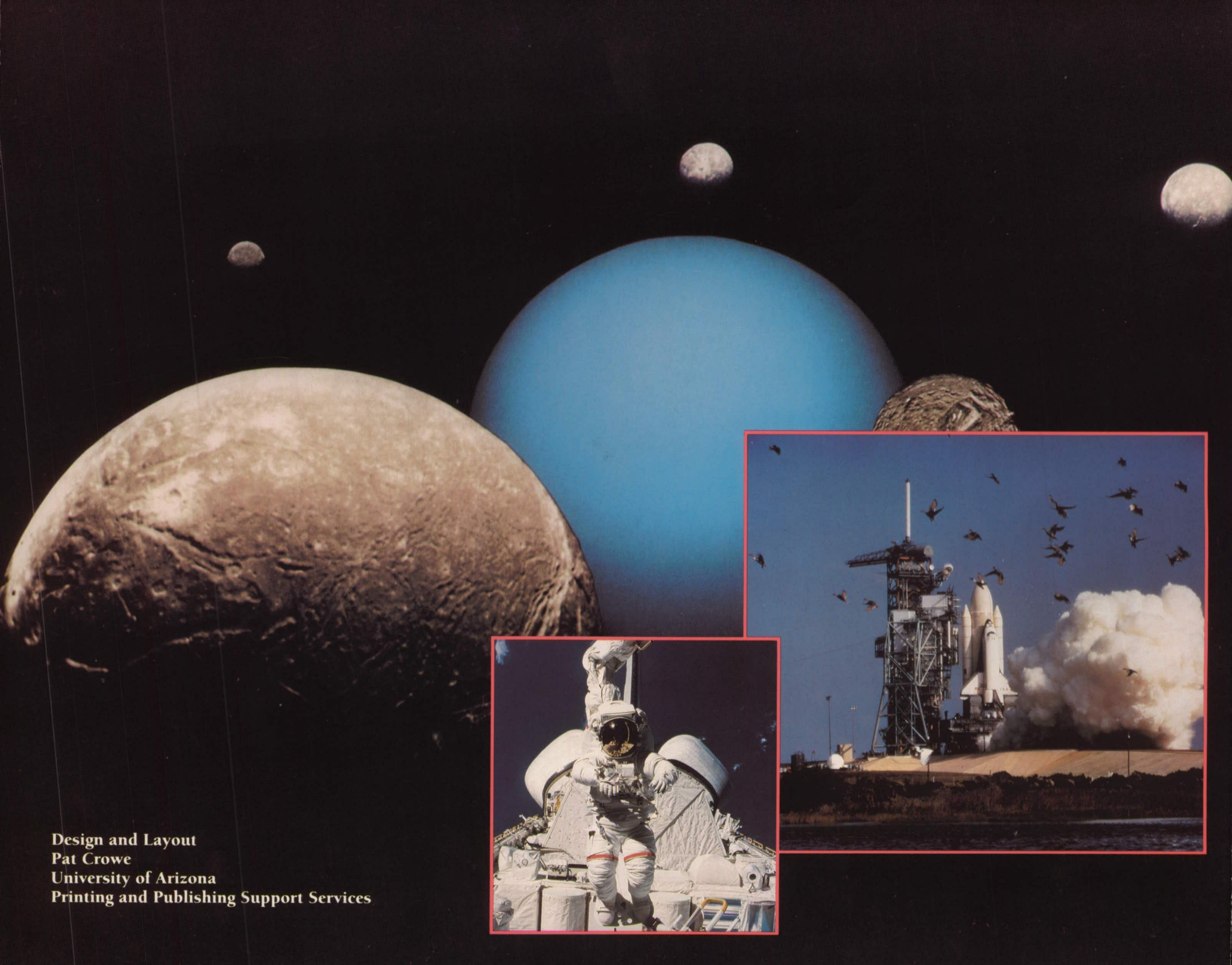


Figure 3

The Center has demonstrated its value to the regional economy by advancing the reputation of the state as a desirable location for space-related businesses and institutions. Estimates of the multiplier effect of NASA research funding on the region indicate a dramatic effect on Arizona's economy. For example, the nearly $2 million in funding received by the Center in 1991 had an estimated economic impact in the state of more than $50 million.

The accompanying figures illustrate the importance of NASA awards to the University, and the Center's success in obtaining a part of that funding. The first figure displays relative NASA funding and University of Arizona funding of SERC since its inception; Figure 2 illustrates NASA's contribution to federal research award activity at the University of Arizona compared with four other agencies for fiscal years 1982 to 1991; and Figure 3 illustrates NASA's share of funding sources of total awards to the University of Arizona for fiscal year 1991.

Additionally, it is anticipated that Space Engineering Affiliate memberships will continue to be renewed and that at least one more will be added each year. This will result in basic industrial support ranging from $50,000 to $100,000 a year. It is expected that special contract research projects sponsored by these companies, as well as by NASA and other government field laboratories, will yield at least $75,000 a year prior to the commitment of substantial federal funds to the SEI program — and several times that much afterward.



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